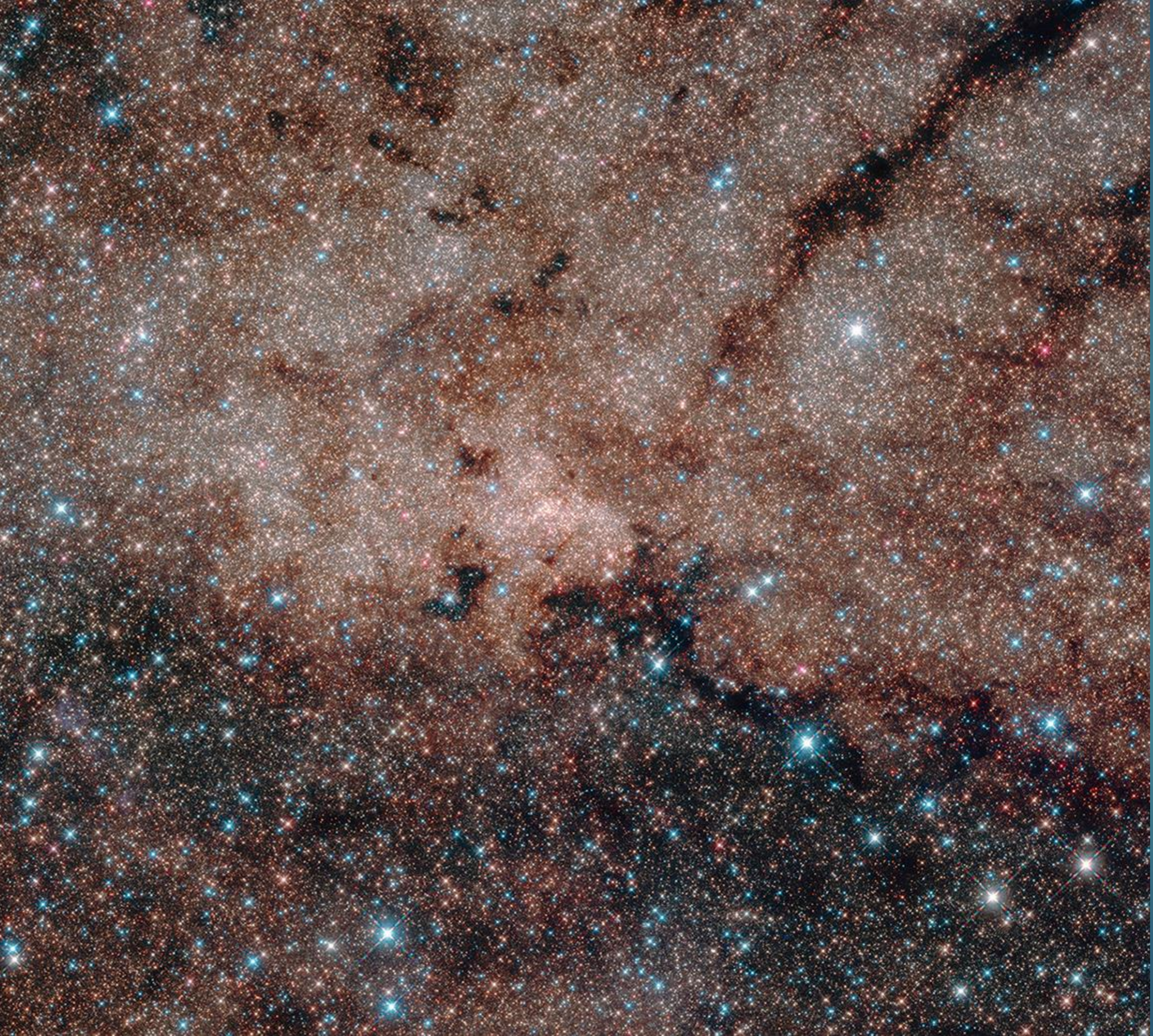
High Resolution Astronomical Spectroscopy Comes of Age

Paul F. Goldsmith

Jet Propulsion Laboratory, California Institute of Technology

Outline of This Talk

- Quick Look at the Interstellar Medium
- Current and Future Facilities for Submillimeter Astronomy
- Astronomical Spectroscopy - from Solar System to Star Formation
- Technological Progress and Challenges



Dust in the interstellar medium (ISM)

Absorbs light from stars at visible & near-IR wavelengths

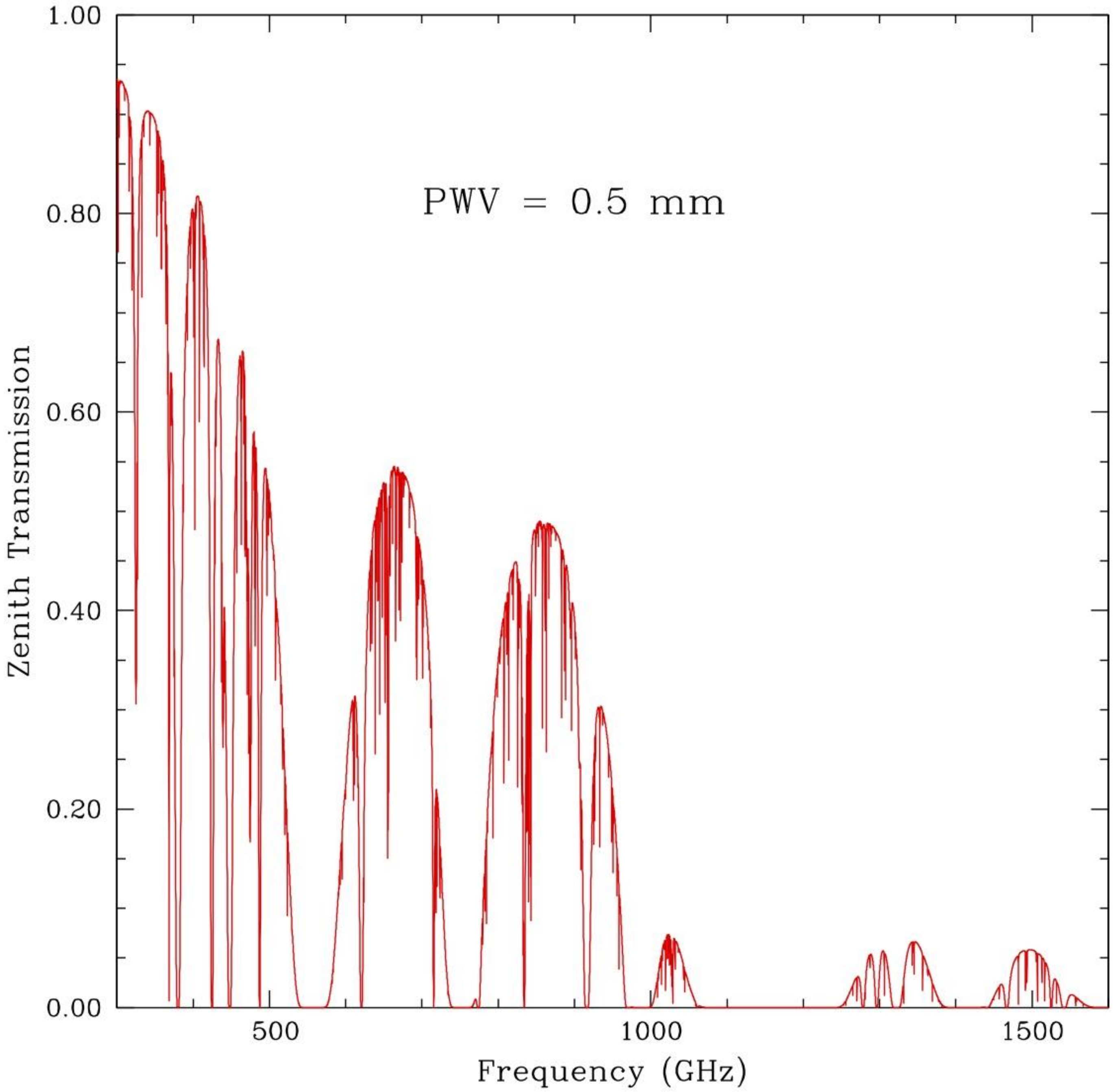
Dust grains have size ~0.1 μm

Critical for the ISM: H_2 molecules formed on grain surfaces

Dust blocks UV and allows rich array of molecules to exist in interstellar clouds

Molecules & atoms radiate at mm & submm wavelengths


Sombrero Galaxy



A Challenge for Submillimeter Astronomy

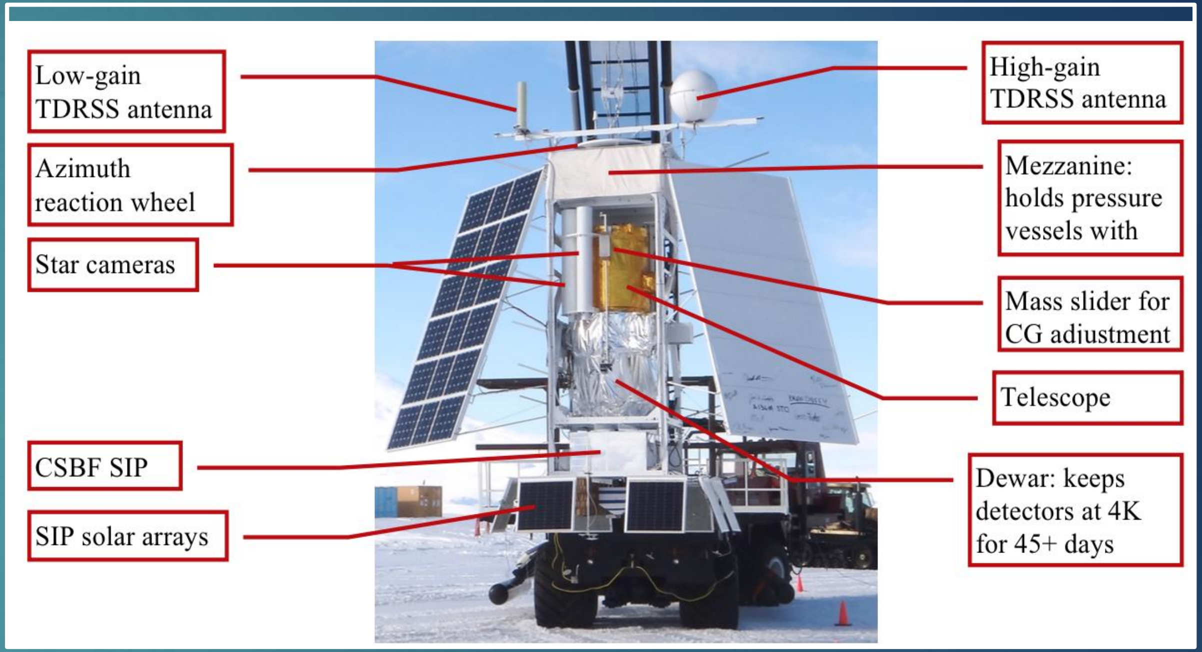
Water vapor (primarily) makes atmospheric transmission ~ 0 from sea level

From very high, dry sites there are "windows" that offer partial transmission

At aircraft altitude (14 km) the situation is much better, but there are still blocked spectral regions

A balloon (40 km) is better, but complete access is possible only from space

To Obtain the Submillimeter High Resolution Astronomical Spectral Line Data You Want – (1) Get Above the Water in the Earth's Atmosphere

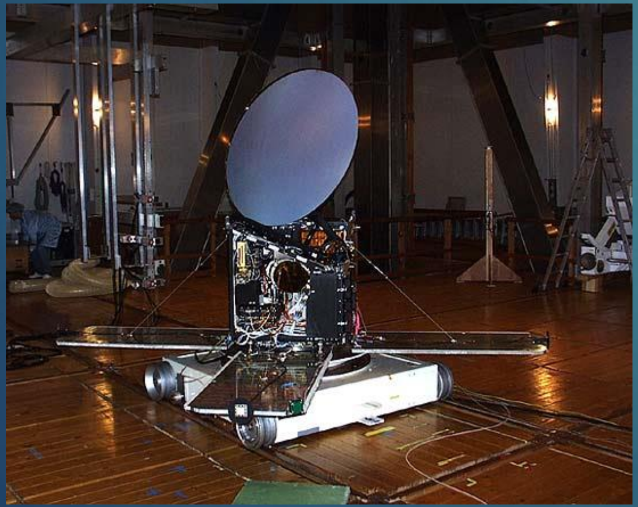


Stratospheric Observatory for Infrared Astronomy (SOFIA)
NASA/DLR
2.5m telescope at ambient temperature @14 km altitude
Multiple instruments

STO2 Balloon – 22 day flight Dec. 2016
40 km altitude
HEB mixers cooled with LHe
Good performance at 1900 GHz

To Obtain the Submillimeter High Resolution Astronomical Spectral Line Data You Want – (2) Get Into Space!

SWAS (1998)
54x68cm offset
Cassegrain
490/550 GHz
CI,O_2,^{13}CO,H_2O
Schottky diode 2nd
harmonic mixers at 150 K



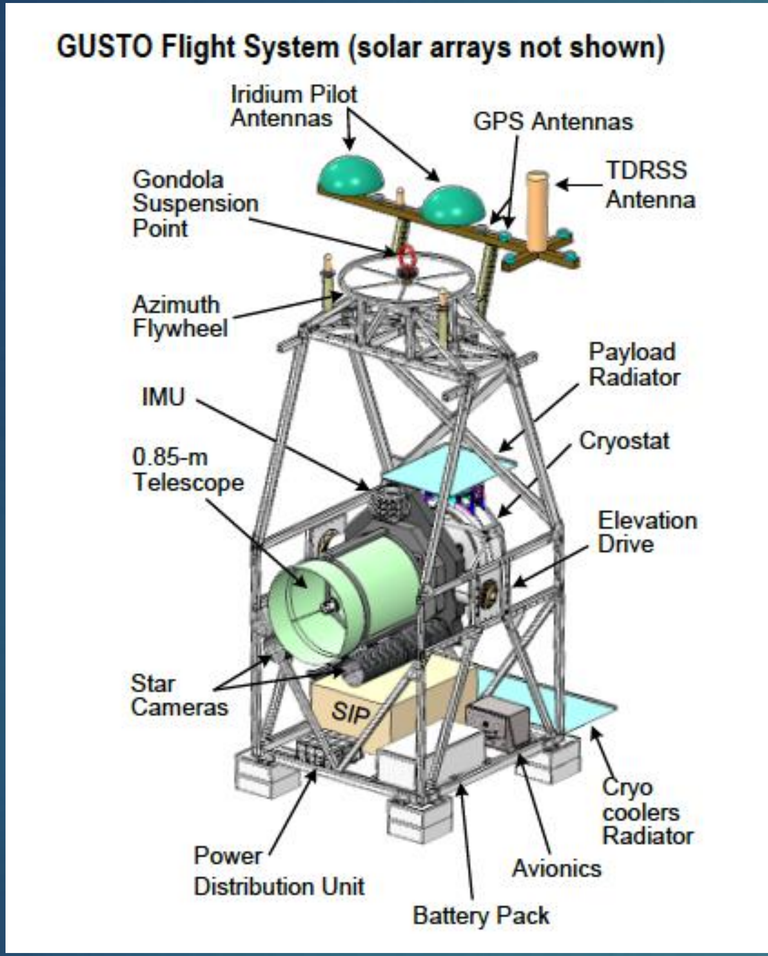
Odin (2001)
1.1m offset
Gregorian
486-581 GHz
tunable
Numerous lines
Schottky mixers
cooled to 140 K

Herschel (2009)
3.5m symmetric Cassegrain
antenna cooled to 80K
480-1900 GHz
SIS and HEB mixers operating at 4K

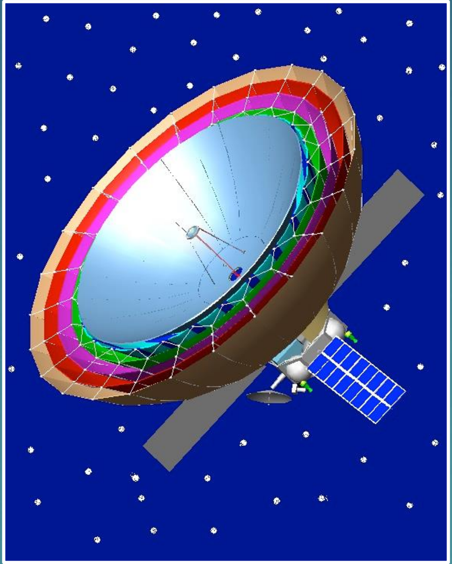
P.F. Goldsmith 2012, Ch. 16 in Imbriale, Gao, and Boccia, eds., **Space Antenna Handbook**, J. Wiley & Sons

Univ. AZ, JPL, ASU, APL, JHU, CfA, Leiden Univ.

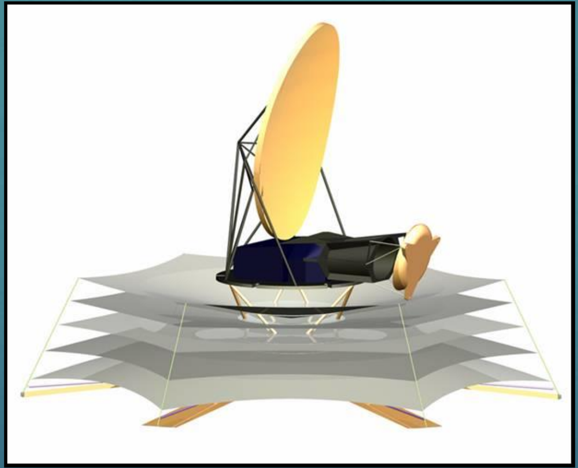
Near-Future and Possible Future Facilities for Submillimeter Spectroscopy



GUSTO
Ultra Long Duration Balloon (100d)
8 HEB mixers at 1460, 1900, and 4745 GHz
Launch Dec. 2021

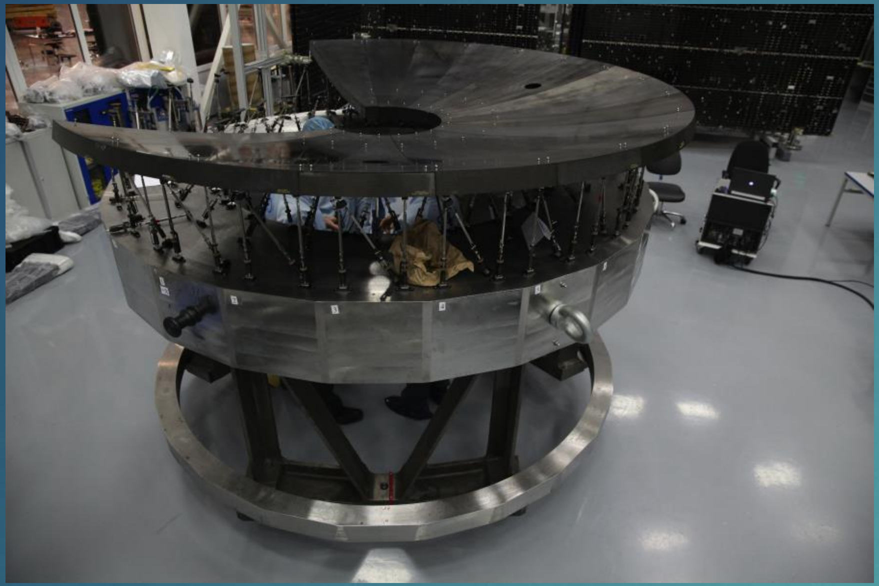


Millimetron (Russia)
10m Deployable Antenna cooled to 6 K
Earth-Space VLBI
Heterodyne spectroscopic instruments TBD



Origins Space Telescope (OST)
6 – 10 m dia. Telescope cooled to < 6 K
2020 U.S. Decadal Study Flagship Mission
Possible heterodyne instrument

Millimetron Development




Why Submillimeter Spectroscopy?

Submm spectral lines provide vital insight into the chemistry and physics of the interstellar medium (ISM) and how clouds of dust and gas in the ISM evolve to form new stars.

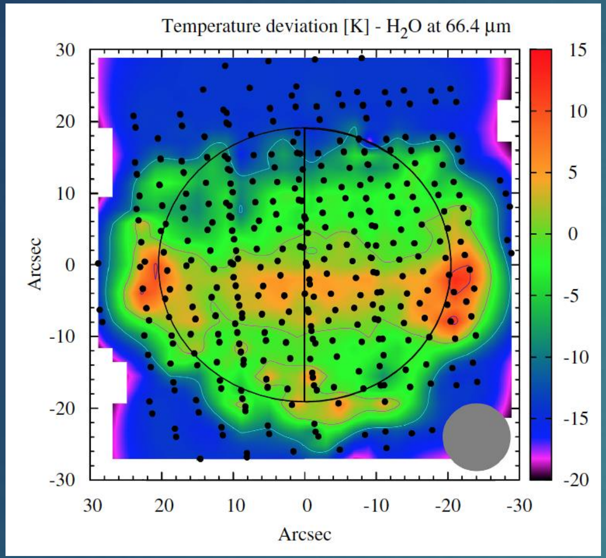
These processes control the evolution of galaxies and formation of planetary systems.

Unique probes

1. fine structure lines: atomic carbon [CI] at 492 and 810 GHz
   ionized carbon [CII] at 1900 GHz
   ionized nitrogen [NII] at 1461 and 2460 GHz
   atomic oxygen [OI] at 2060 and 4745 GHz
2. Higher rotational lines of key tracers including CO allowing study of interstellar shocks, outflows from young stars, and protostellar disks
3. Key biogenic molecule – **WATER (H_2O)** and others (HF, ArH, O_2,…)

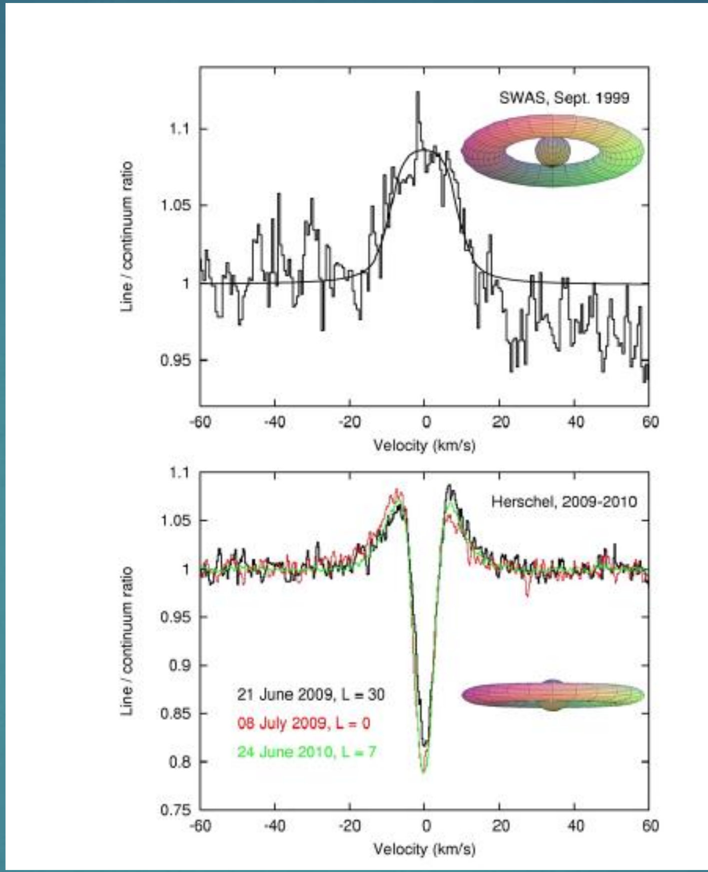
High spectral resolution allows measuring motions within these clouds, cores, and disks, and thus to understand what they are doing

Water Throughout the Solar System



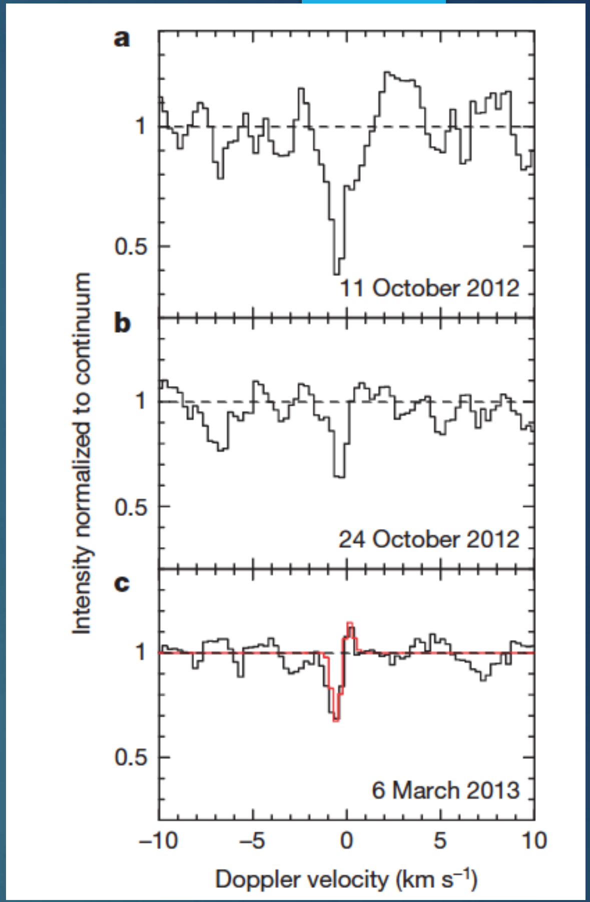
In Jupiter's atmosphere
Cavalié et al. (2010)
Herschel/PACS

Comet Shoemaker Levy impact July 1994



In **Saturn's moon Enceladus**
Hartogh et al. (2011)
557 GHz 1_{10}-1_{01}

SWAS and *Herschel*/HIFI



In **dwarf planet Ceres**
Küppers et al. (2014)
Herschel/HIFI 557 Ghz

ORION – A Case Study of the Nearest Region of Massive Star Formation

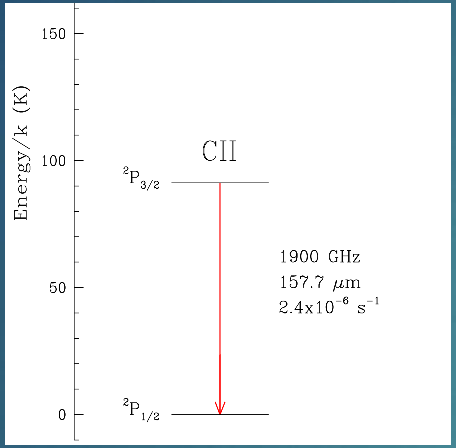

Visible – stars; ionized gas


Near-IR hot dust +PAH


FIR(Submm)-cool/warm dust

Thanks to
X. Tielens
C. Pabst
S, Suri

[CII] 158 μm Fine Structure Line



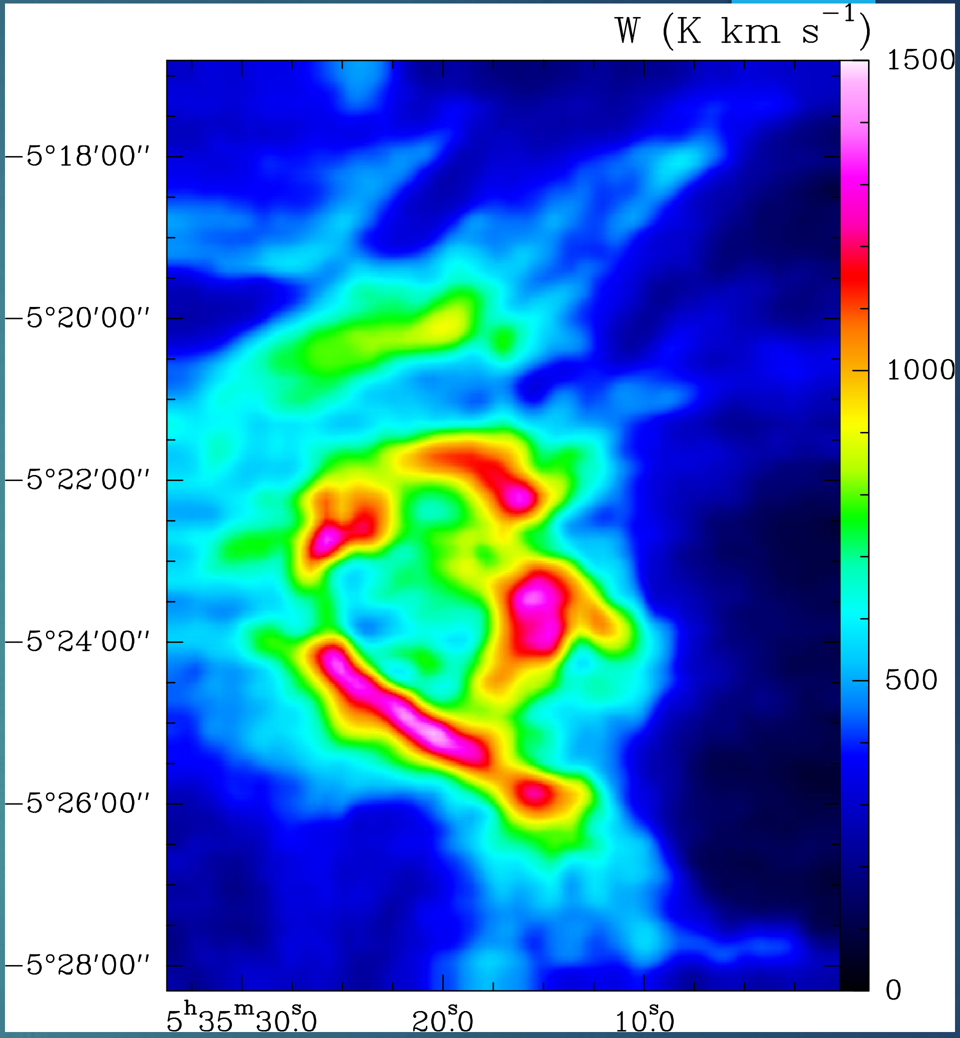
Most luminous FIR Spectral Line in Milky Way and other galaxies

Primary coolant of diffuse ISM – regulates temperature of atomic clouds

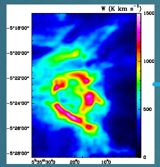
[CII] also from regions where hydrogen is ionized and from boundaries of dense clouds

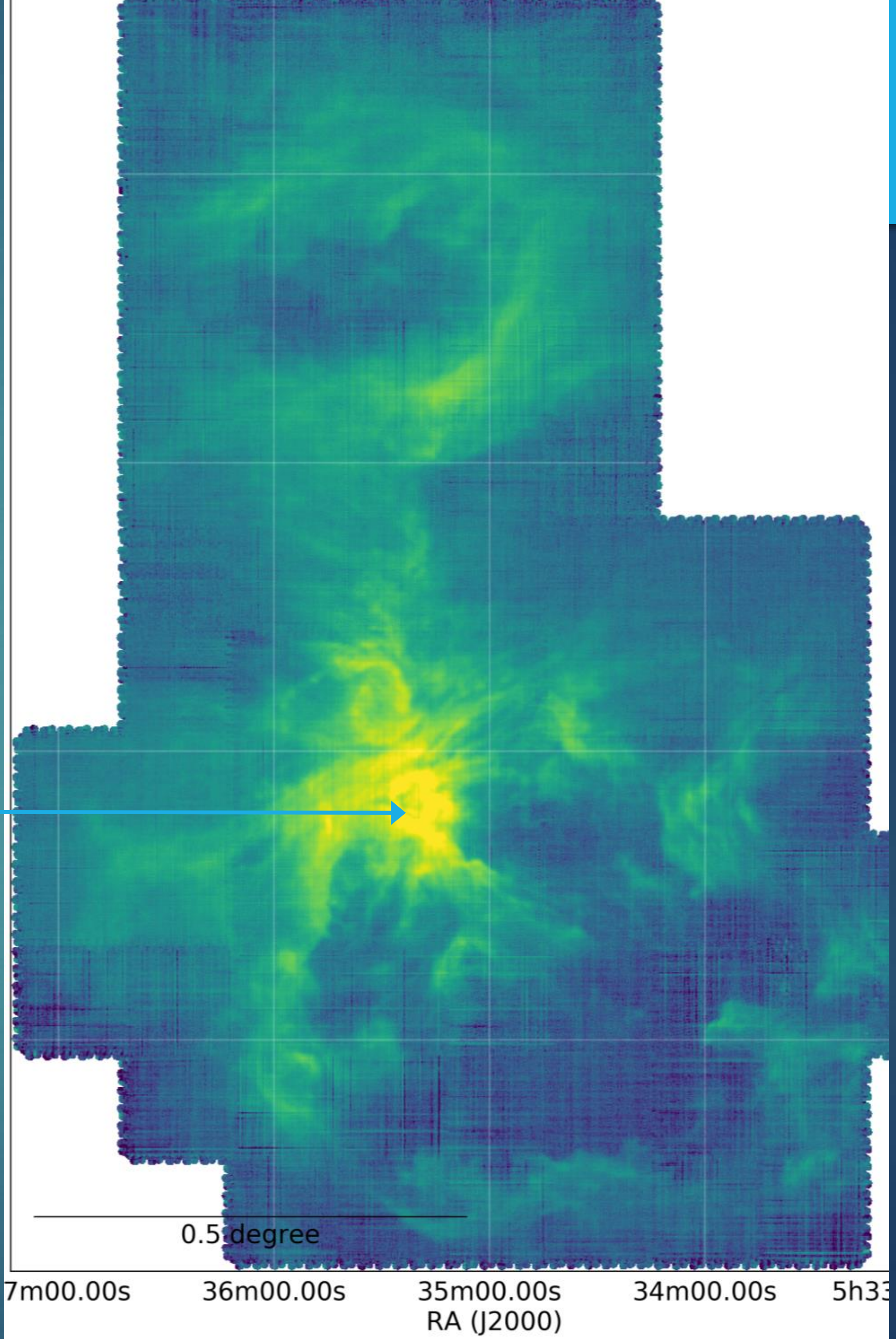
Excellent probe of star formation

10’
1.2 pc

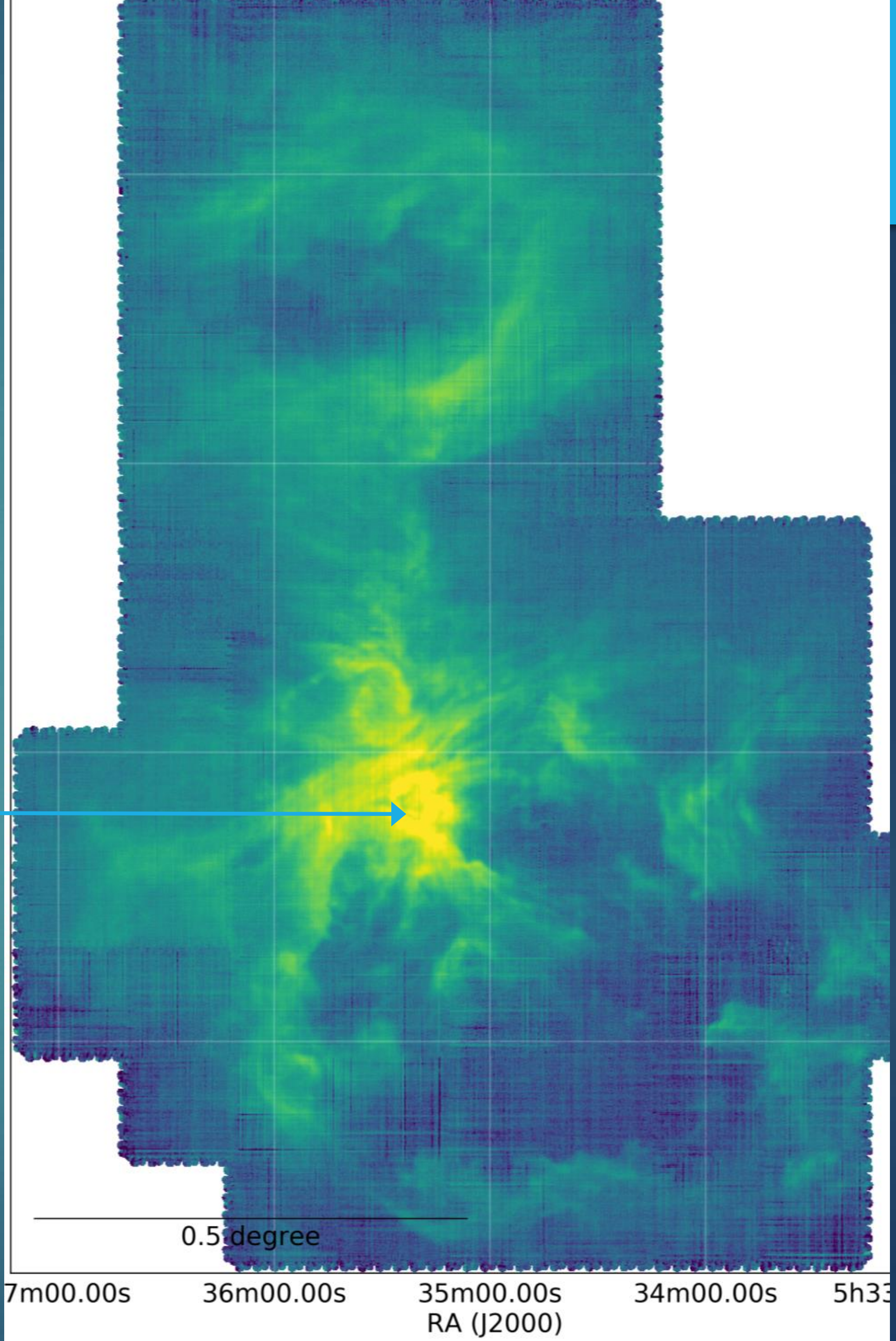


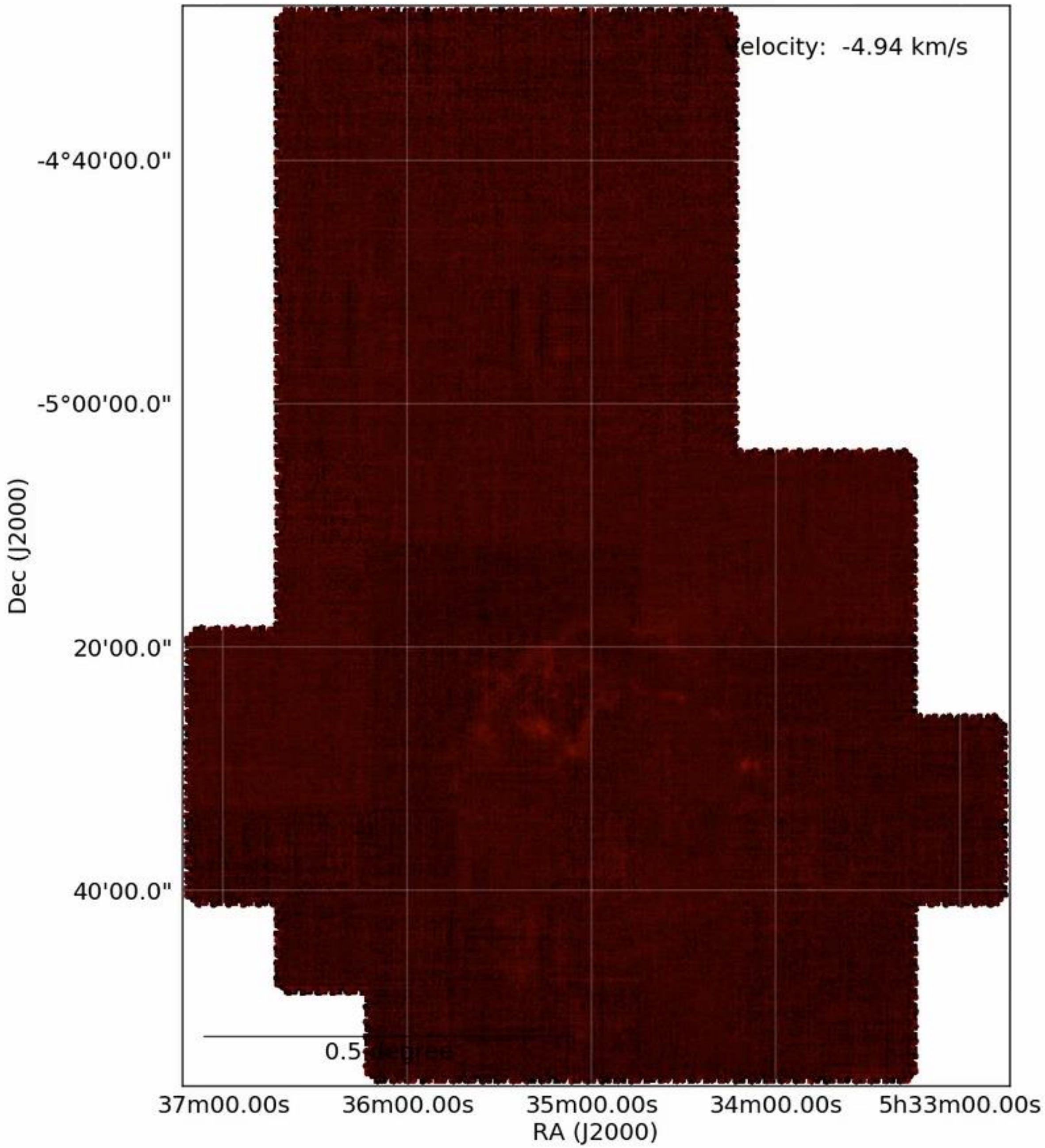
[CII] Integrated Emission in Orion from Herschel/HIFI Goicoechea et al. (2015)





9 hours with Herschel/HIFI
1 element receiver
Undersampled map

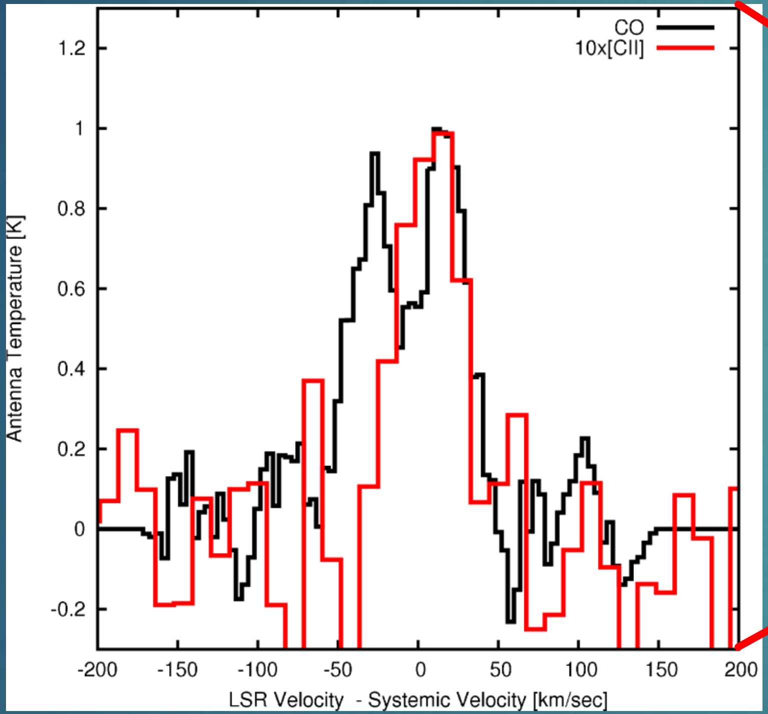

0.5 degree
7m00.00s
36m00.00s
35m00.00s
34m00.00s
5h33
RA (J2000)

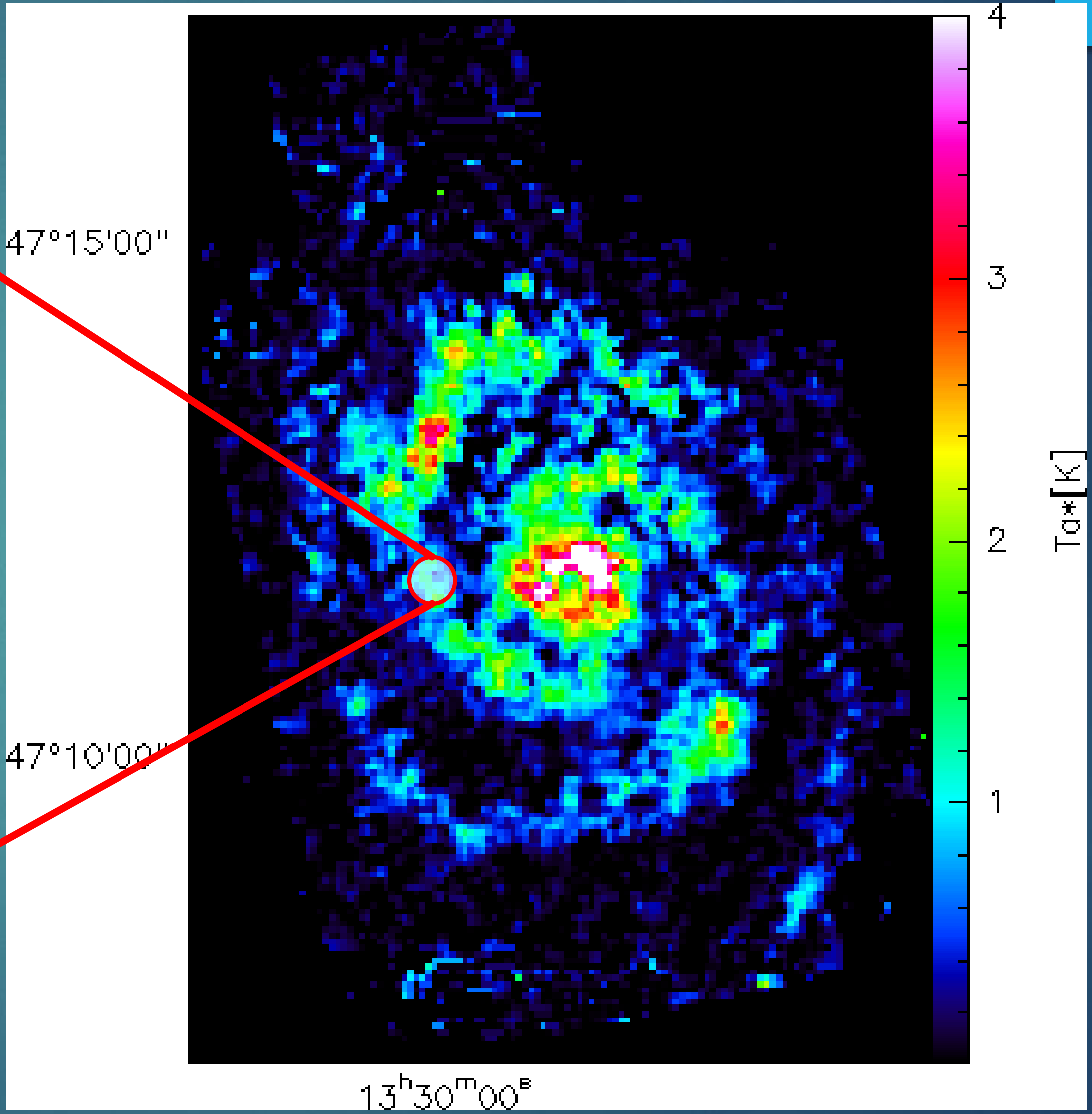


40 hours with SOFIA upGREAT
7-element receiver
Fully-sampled image
2.5 million spectra

X. Tielens, C. Pabst, S. Suri

Imaging Nearby Galaxies – M51 [CII] 158 μm



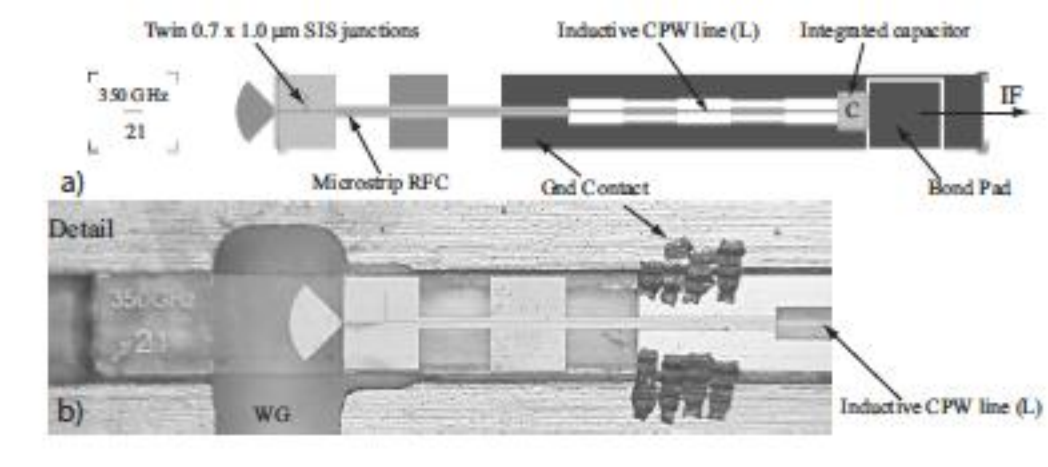


CO and C^+ have VERY different profiles
Ionized carbon “downstream” from CO
Spiral density waves -> Young stars ->
Ionized gas
[CII] from SOFIA Impact Project J. Pineda (PI) 20+ hr obs. time

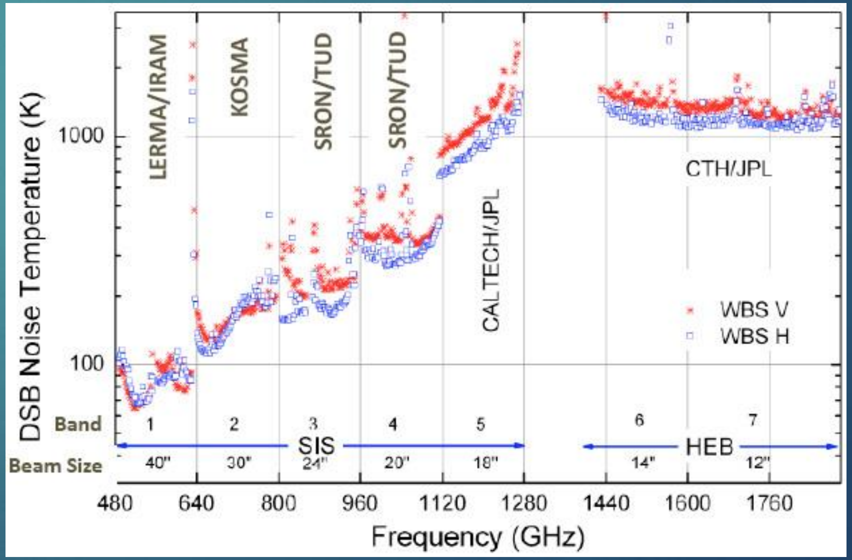
Technology Enabling Submm Spectroscopy

Enormous progress is last decades in ALL critical areas

1. High Sensitivity Mixers: SIS (excellent to ~ 1000 GHz), HEB (good but could be better)
2. Local Oscillators – few μW per mixing element, tunable, spectrally pure
3. Broadband IF amplifiers
4. Digital spectrometers –multi-GHz bandwidth



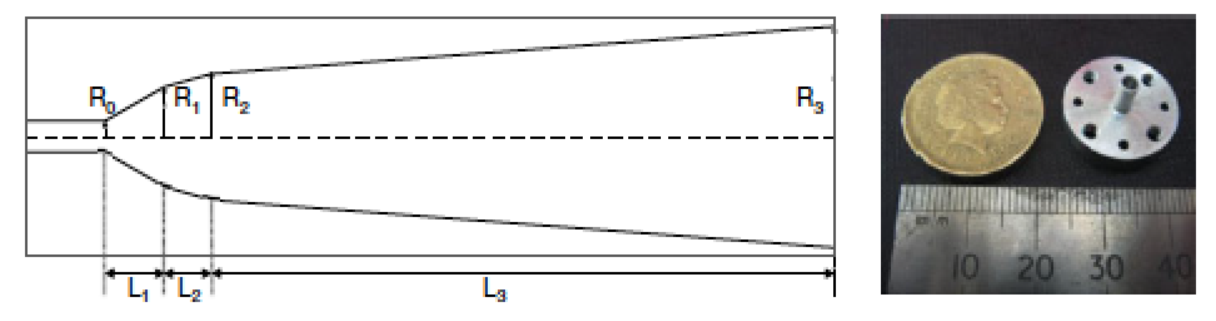
Balanced 350 GHz SIS mixer (Kooi et al. 2011)



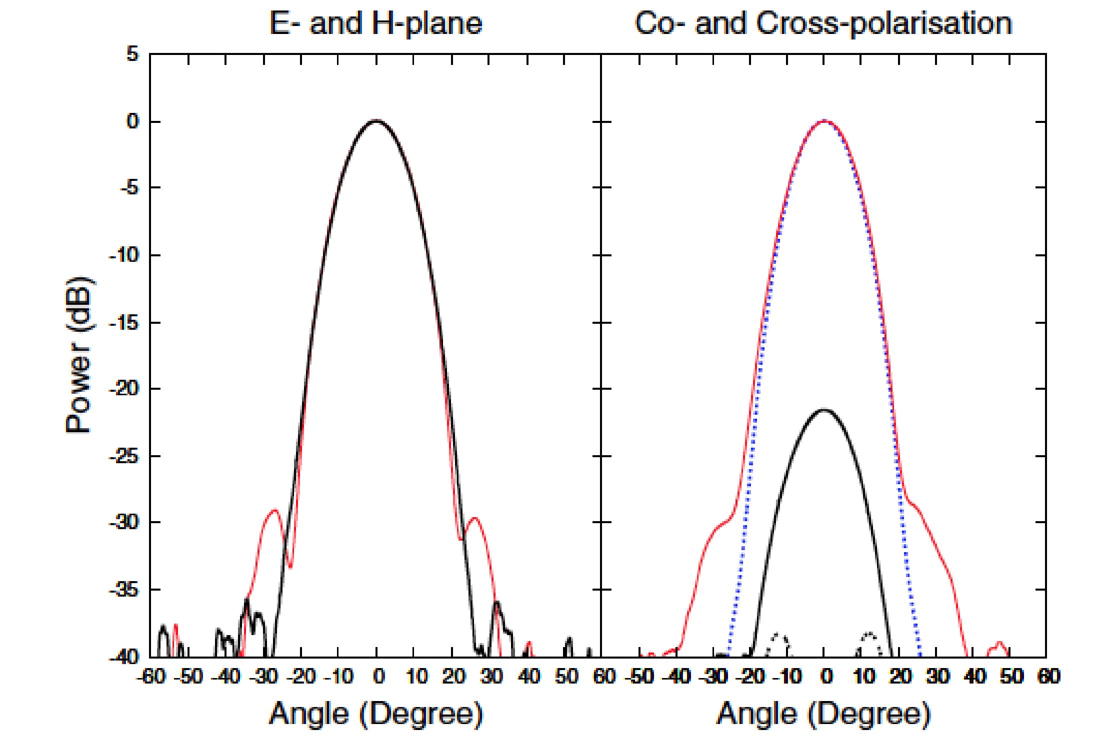
Current challenge: Large-format Heterodyne Focal Plane Arrays (HFPAs)

Feed Elements – multisection smooth-walled feedhorns are now well-understood, offering excellent performance over substantial bandwidths (~30%). They are excellent for submillimeter wavelengths, offering performance comparable to scalar feedhorns with ease of construction comparable to e.g. diagonal feedhorns

For fundamental reasons, high-quality feeds in an array produce beams on the sky separated by a MINIMUM angle *Δθ* = 2. FWHM beam width



(a) (b)



700 GHz feedhorn
Tan et al. (2012) J. Infrared Milli Terahz Waves

Feeds and Beams on Sky

For fundamental reasons, high-quality feeds in an array produce beams on the sky separated by a MINIMUM angle $\Delta\theta$ = 2. FWHM beam width

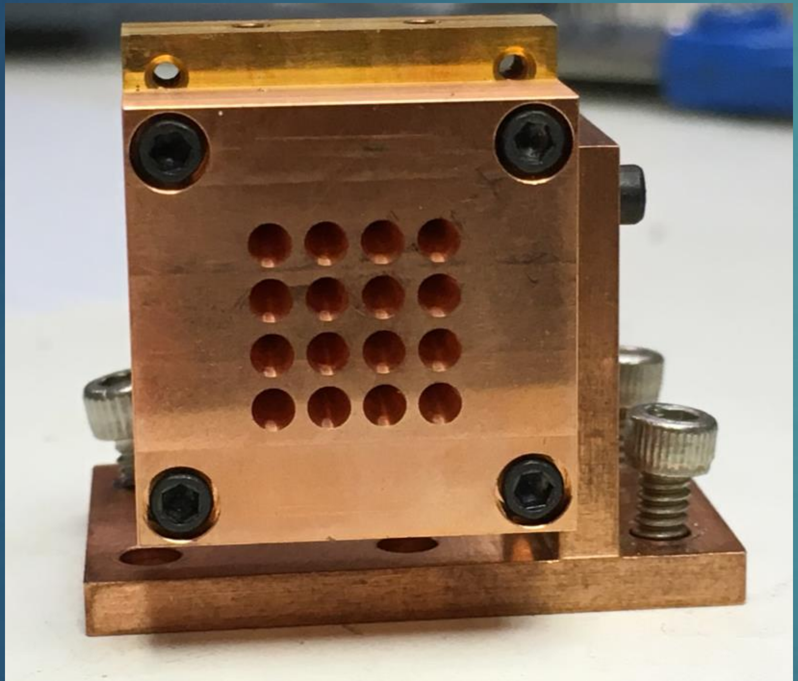
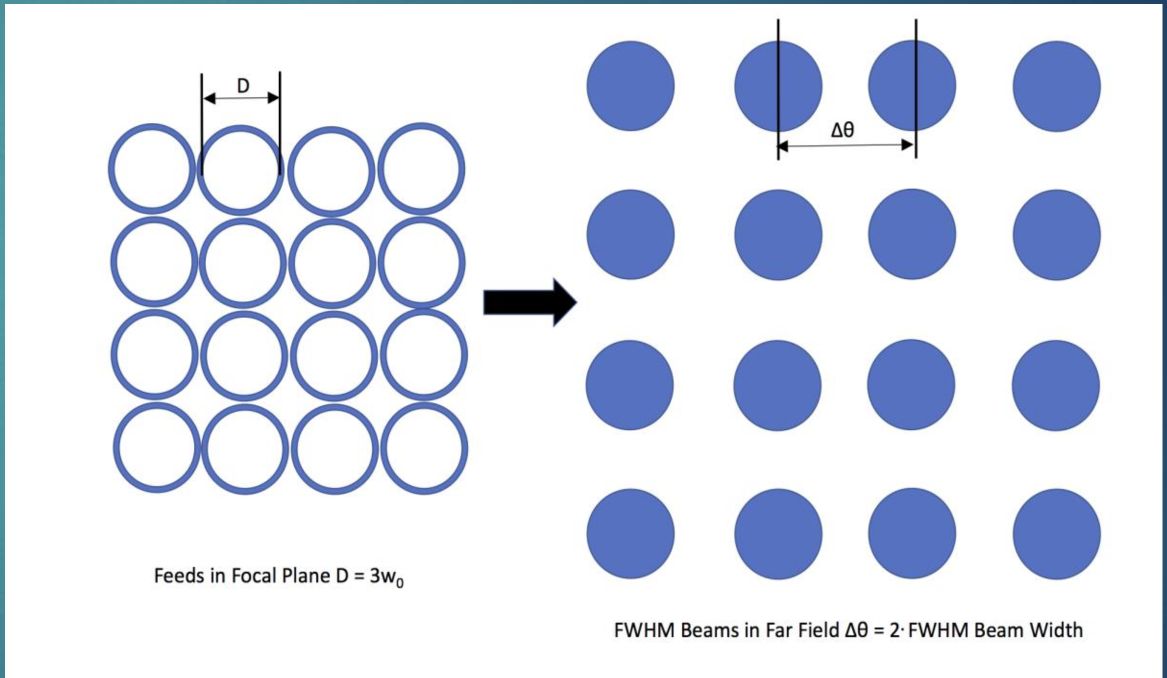
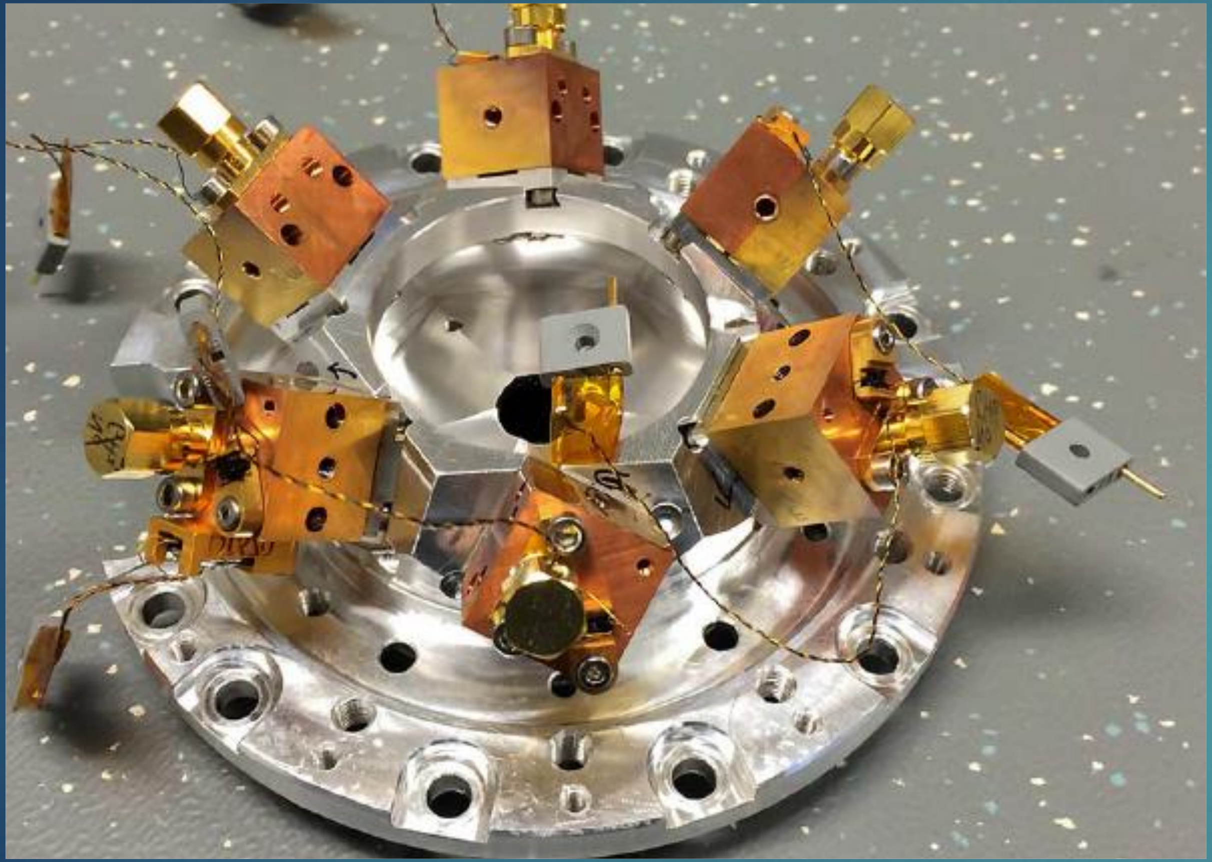


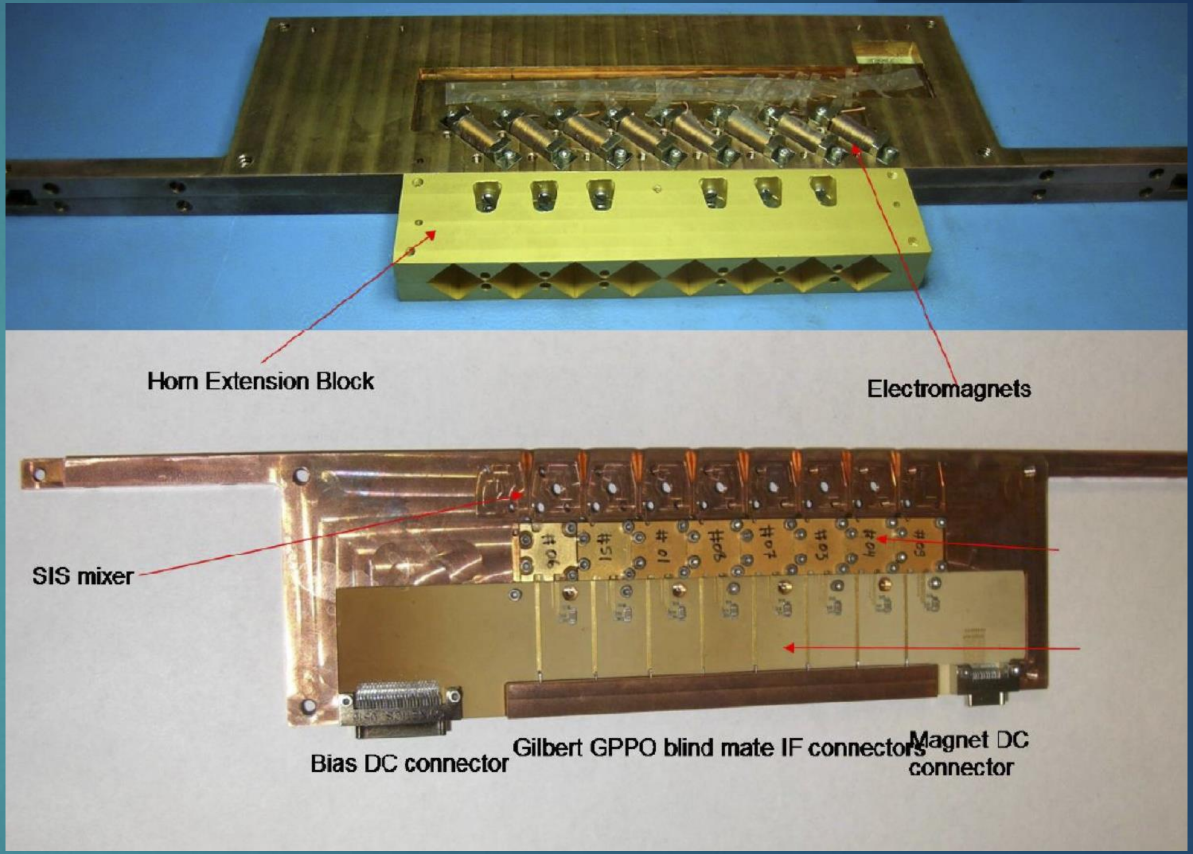
Figure courtesy of Jon Kawamura



Close-packing of feedhorns is desirable. Hexagonal Geometry is not significantly better than Cartesian.

HFPA Mixers: Different Approaches





7 pixels of one polarization of upGREAT LFA
Risacher et al (2016).   Operates at ~2000 GHz
HEB mixers; spline feedhorns

One row of pixels from Supercam array
Groppi et al. (2008). Operates at ~345 GHz
SIS mixers (note magnets); diagonal feed horns

Local Oscillators for Submillimeter Heterodyne Arrays

CURRENT OPTIONS

1. Quantum Cascade Lasers (QCL) – almost any frequency; ample power, but limited tunability, high DC power dissipation, require cooling, and non-trivial to frequency or phaselock.

2. Frequency-multiplied sources – limited to x2 and x3, so cascaded stages required to reach above 1000 GHz. >10% tunability. Power adequate for modest number of mixers.

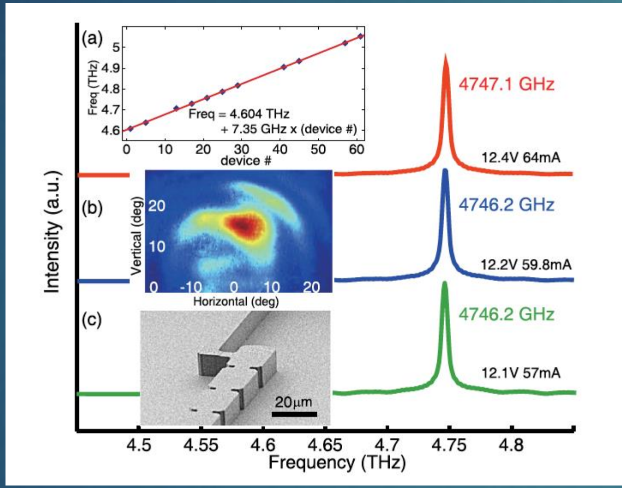
While complex, an “ideal” array system has independently adjustable power for each mixer. Readily achieved with multiplier cascades with individual final chains.

See Ligan, Liu, and Wang (2017) for recent review.

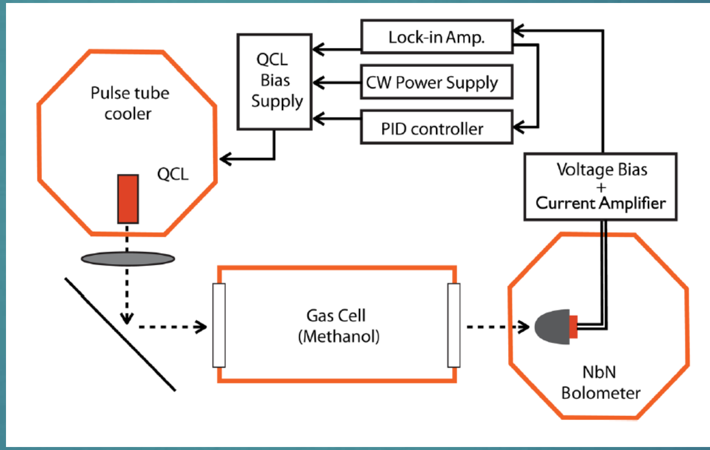
Quantum Cascade Laser (QCL) – multiple strongly-coupled quantum wells allow electron transitions between resulting subbands. With resonator structure, a relatively clean output results, having some current and temperature tunability.

Multiple lasers designed to operate at different (adjacent) frequencies can be used to increase frequency coverage

Submm QCLs must be cooled to 10 -12 K (sometimes higher); dissipate significant DC power but provide 200 – 500 mW while providing 200 – 1000 µW submillimeter power



Kloosterman et al. (2013)
QCL dissipates 700 mW @ 10 K

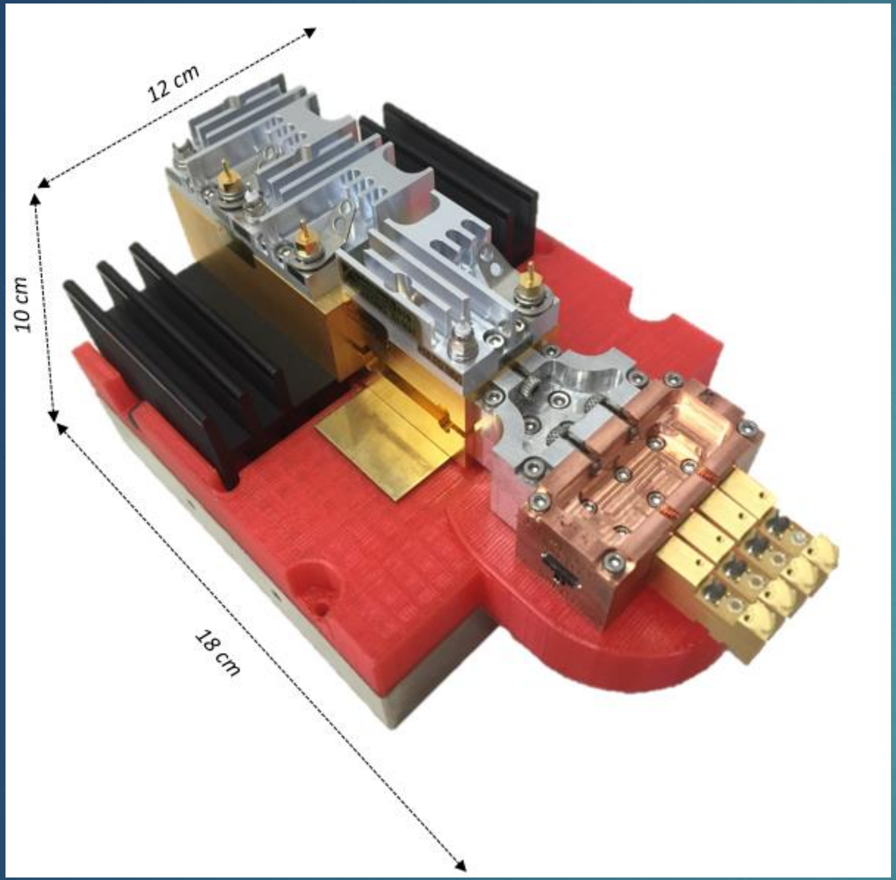


Frequency locking: Ren et al. (2012)
Phase Locking: Rabanus et al. (2009)

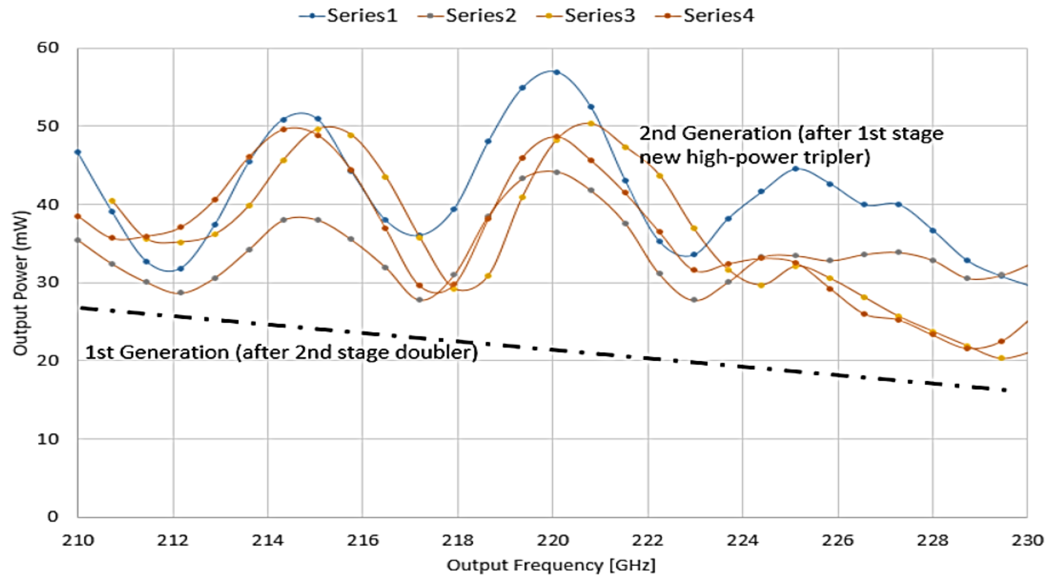
QCL used as LO for HFA channel of 7-element upGREAT receiver on SOFIA

Risacher et al. (2011); Richter et al. (2015)

2nd Generation 1.9 THz 4-pixel LO System



2nd Generation 1.9 THz 4-Pixel Frequency Multiplied Chain



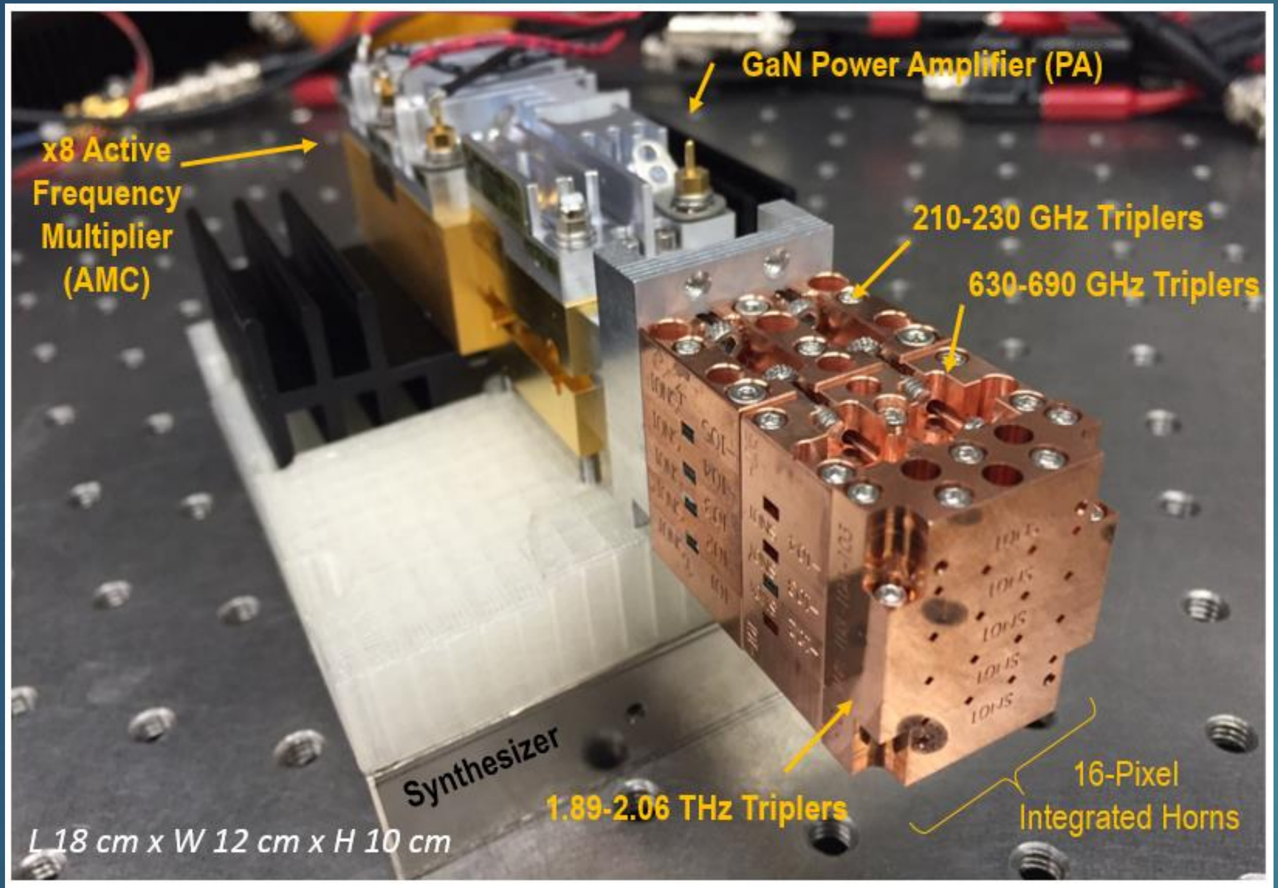
X3X3X3 Architecture

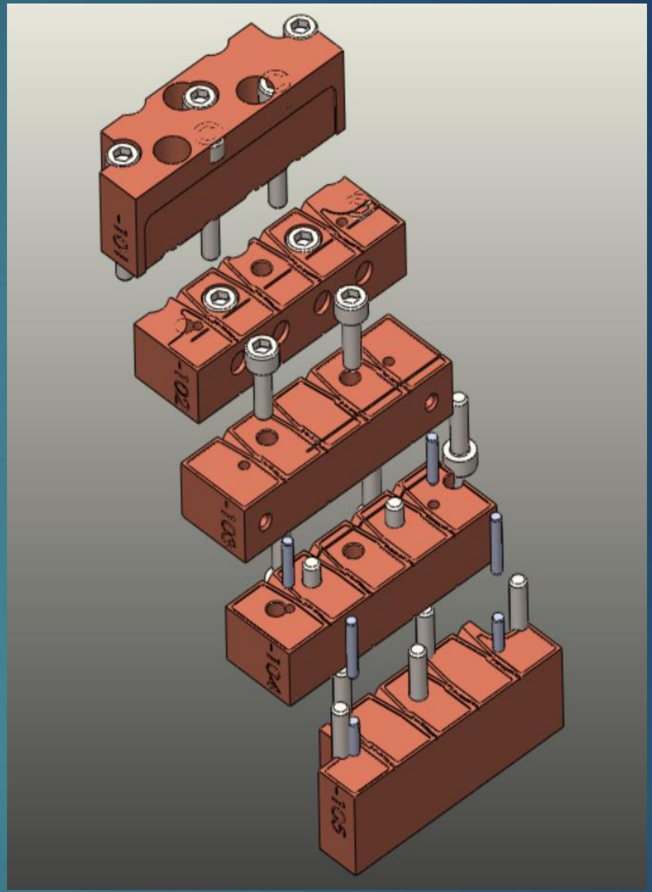
Power Consumption= 5.5 Watts/pixel

Main improvements with regards 1st generation are (i) compactness and (ii) increase in power delivered at the output of the X3 1st stage (Gen 2) compared to the output of the X3X2 stage in Gen 1.

J. Siles, JPL

16-Pixel 1.9 THz LO System: STACKING





The LO module can be mounted with either two or four 1x4 pixel layers vertically stacked to form 8-pixels or 16-pixel configurations..

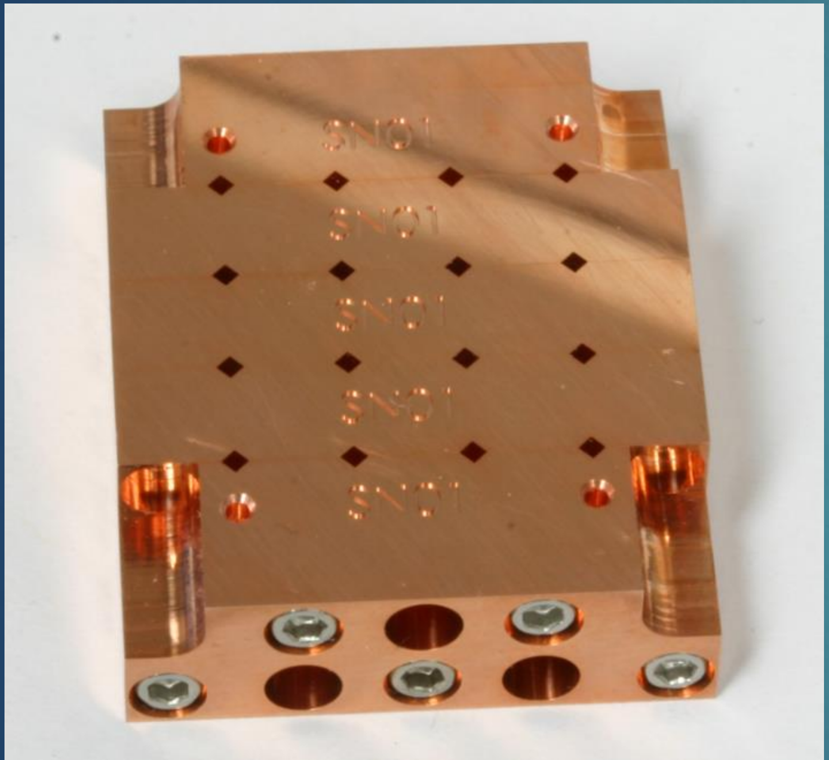
X3X3X3 Architecture

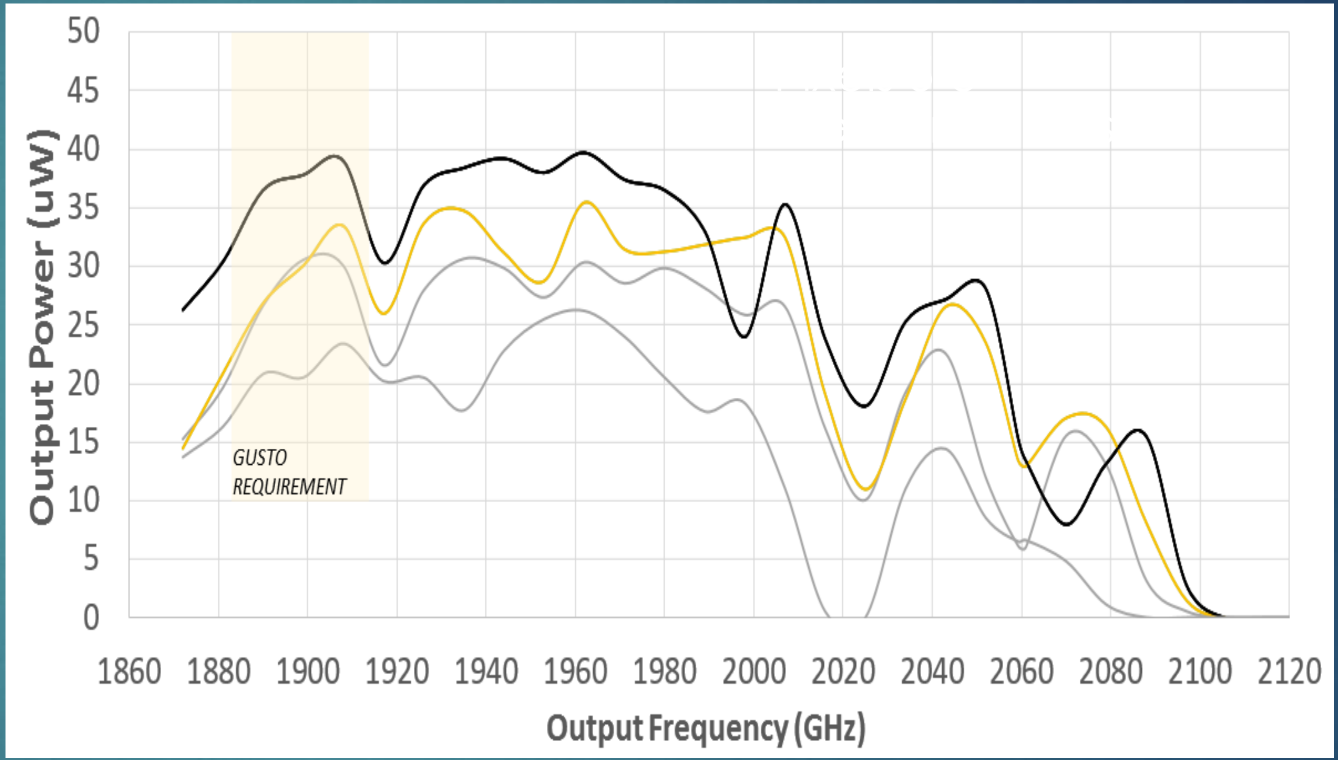
Power Consumption= 2.3 Watts/pixel or 1.25 Watts/pixel using W-band CMOS synthesizers

J. Siles, JPL

16-Pixel 1.9-2.06 THz LO System

High power/large bandwidth source with no cooling required





1st Generation 1.9 THz 16-Pixel Frequency Multiplied Chain

X3X3X3 Architecture

Power Consumption= 2.3 Watts/pixel or 1.25 Watts/pixel using W-band CMOS synthesizers

J. Siles, JPL

Submm Heterodyne Focal Plane Arrays (HFPAs)

Name	Frequency (GHz)	$N_{element}$	Mixer Type	LO Injection	Image Rotation	SSB Filter	Telescope	Ref	Comments
CHAMP	460 - 490	16	SIS	FG+MP		X	CSO 10m	1	other telescopes
Pole STAR	810	4	SIS	ML+MP			AST/RO 1.7m	2	
SMART	490/810	8/8	SIS	CFG+MP	K		KOSMA 3m	3	2-band; also NANTEN 4m
Desert STAR	345	7	SIS	CFG+DS			HHT 10m	4	
CHAMP+	670/860	7/7	SIS	CFG+MP	RX	X	APEX 12m	5	Dual band
SuperCam	345	64	SIS	WG+DS			HHT 10m	6	Also APEX
HARP	345	16	SIS	ML+DS	K	X	JCMT 15m	7	
upGREAT	2000/4700	14/7	HEB	FG+WG	K		SOFIA 2.5m	8	Dual Band

Sensitive spectroscopic systems
- Individual elements
- Now HFPAs

Terms

SIS	Superconductor-Insulator-Superconductor
HEB	Hot Electron Bolometer
MP	Martin-Puplett Interferometer
FG	Fourier Grating
CFG	Collimating Fourier Grating
DS	Dielectric slab beam splitter
WG	Wire grid beam splitter
ML	Meander Line
K	K-mirror for image rotation
RX	Receiver rotated
SSB	Single Sideband filter – generally dual-beam interferometer

Geometry

7 &14 element arrays are hexagonal format
2^n element arrays utilized Cartesian format

References

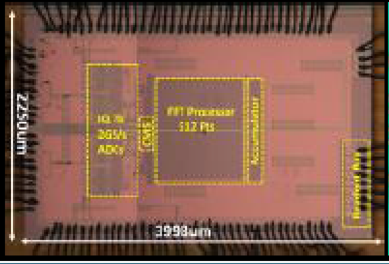
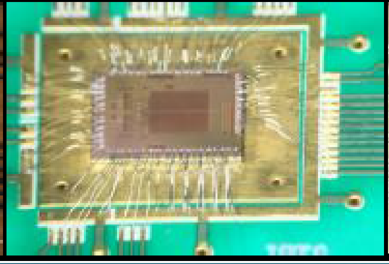
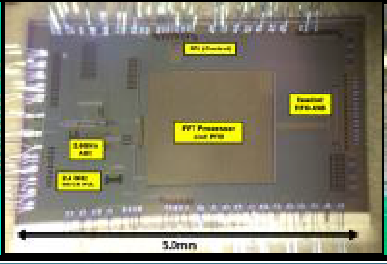
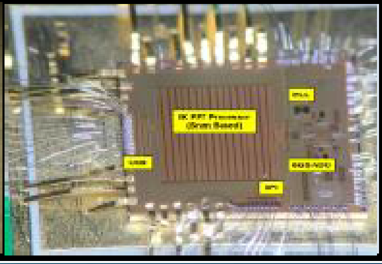
1 Groppi+ (2001)
2 Guesten+ (1998)
3 Graf+ (2002)
4 Groppi+ (2003)
5 Kasemann+ (2006)
6 Groppi+ (2008)
7 Buckle+ (2009)
8 Risacher+ (2016a,b)

1

An Important Requirement for HFPAs is Spectroscopic Processing Capability

- The current SOA is to use FPGAs (Roach) which work well and are flexible
- For large-N arrays (even at mm wavelengths) with multi-GHz coverage, and > 1000 channels, size & power are challenges
- Power and weight are highlys critical for space missions, and even suborbital platforms (aircraft, ballooncraft)
- A rapidly-developing alternative is **CMOS VLSI** Application Specific Integrated Circuits (**ASICS**) "System on Chip" (**SOC**)
- Far more efficient than FPGAs in terms of space and utilization, but you give up flexibility
- JPL has been pursuing this route with UCLA and Broadcom

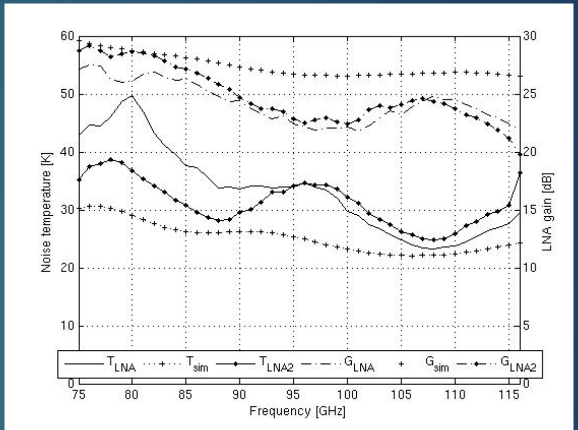
Integrate digitizer, processor, memory, and output interface

Chip Version	UCLA SII 2014	UCLA SIIb 2015	UCLA SVI 2016	UCLA SVII 2017	UCLA SVIII (FY17 APRA Proposal)
Processor Type	SoC FFT Spectrometer	SoC FFT Spectrometer	SoC FFT Spectrometer	SoC FFT Spectrometer	SoC FFT Spectrometer
Bandwidth	0.5 GHz	1.0 GHz	1.5 GHz	3.0 GHz	6.0 GHz
Channel Count	256	512	1024	4096	8192
Power Consumption	188 mW	488 mW	652 mW	1620 mW	1100 mW
Semiconductor Technology	65nm CMOS SoC	65nm CMOS SoC	65nm CMOS SoC	65nm CMOS SoC	28 nm HPC SoC
Integrated Digitizer?	Yes	Yes	Yes	Yes	Yes
Chip Photograph					

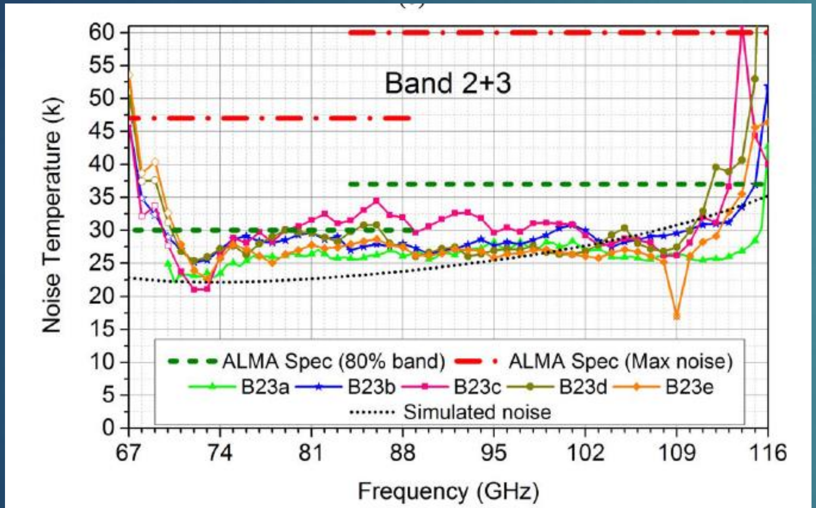
A Technology for MM HFPAs and Possibly SUBMM HFPAs is MMIC Amplifiers

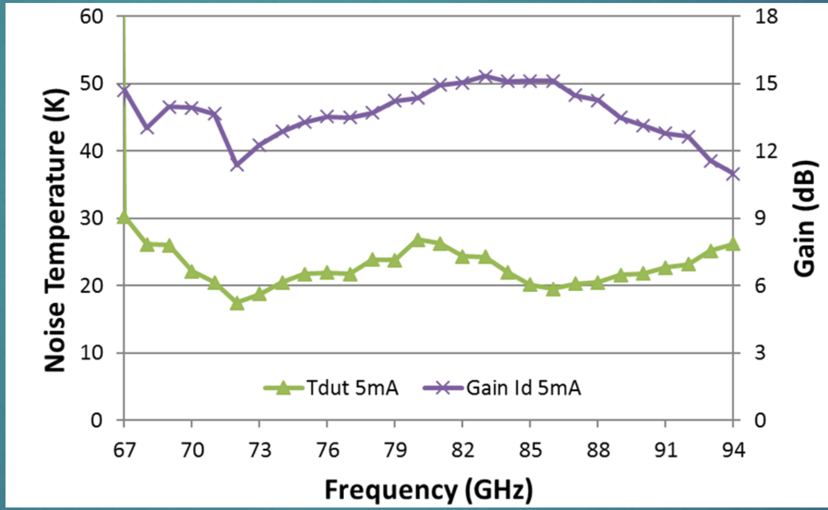
- Amplifiers dominant through microwave and cm-wave regions of the spectrum
- SIS mixers currently have lowest noise temperatures for f > 100 GHz
  - Limited (but large IF bandwidths (~ 10 GHz)
  - Become more complex for balanced and sideband selective configurations
  - Require cooling to temperatures below 4 K
- Can MMIC amplifiers compete?
  - Large (30%) fractional bandwidths
  - Work at any temperature but T_n drops going as low as 15 K
  - Relatively easy to integrate into arrays (downconversion after amplifier is noncritical)

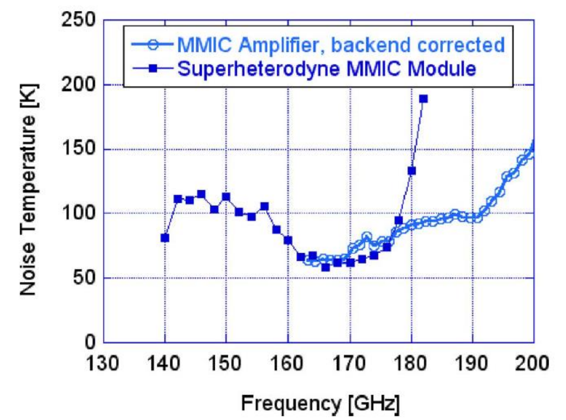
- MMIC amplifiers offer SOA noise performance up to 120 GHz
- Higher frequencies much less explored
- Reason to be optimistic, IF development continues



Varonen et al.(2013)
T_{amb} = 27 K







Cuadrado-Calle et al. (2017)
T_{amb} = 20 K

Kangaslahti et al. (2017)
T_{amb} = 20 K

Samoska (2011) T_{amb} = 20 K